NTSC component separation via Hadamard transform

M. Colef
J. Barba

Indexing terms: Colour video signal coding, Hadamard transform, NTSC component separation

Abstract: The authors present a technique for separating the NTSC composite signal into its components (Y, I, Q) by applying an $N \times N$ Hadamard transform directly to the composite signal sampled at four times the colour subcarrier. We show that the Y, I, Q component signals are mapped into specific areas in the Hadamard domain. Component separation is achieved by assigning particular transform coefficients to each component signal. Simulation results of component separation applied to five colour images and one black and white test pattern are presented. Both signal to noise ratios and subjective results are presented. The results indicate that no noticeable degradation is expected in typical colour images.

1 Introduction

Technological developments in digital hardware (both complexity and speed) have made digital processing of video signals cost competitive with analogue techniques. This is especially true in the area of bandwidth compression of NTSC composite video signals where transform coding has found extensive use [1, 2]. Transform coding of the NTSC composite signal is generally performed individually on the less correlated YIQ signals, thereby requiring the coder to contain the additional hardware to decompose the composite signal into its components. Traditionally, the separation of luminance information has been achieved by the use of overlapping low pass filters and band pass filters have been used to extract the chrominance signals. Currently, comb filters are used to separate the NTSC signal into its components.

Some researchers have investigated transform coding of the NTSC composite signal directly [3–5] by defining the transform data block boundaries, taking into consideration the phase of the subcarrier, so as to maximise the correlation among the samples within the block. This results in compacting most of the signal energy, of both the luminance and chrominance components, towards the low frequency coefficients in the transform domain. These techniques require that the phase of the subcarrier be taken into consideration, but does eliminate the need for additional hardware to separate the NTSC composite signal into its components. However, by compacting the signal energy of the three component signals into the low order coefficients, these techniques do not exploit the fact that, on average, the luminance and chrominance signals occupy different portions of the spectrum; this is precisely one of the reasons for the choice of the colour subcarrier. Consequently, these techniques do not offer the flexibility of coding each component separately.

In this paper we show that, by taking into consideration the sampling phase of the NTSC composite signal at four times the colour subcarrier, the YIQ components are concentrated into different areas of the transform domain. This allows individual coding of the component signals by manipulating the bit allocation of those coefficients pertaining to each particular component, as opposed to use of a decoder and individual processing circuits as is typical. A disadvantage is that sampling at four times the colour subcarrier frequency reduces the achievable compression. At the receiver, all that is required is to perform an inverse Hadamard transform to generate the NTSC composite signal. The Hadamard transform is attractive because it is easy to implement in hardware [6, 7], and the theory is easy to visualise.

2 Hadamard spectrum of the *Q* and *I* signals

The relation between an $N \times N$ array, $f(x, y)$, representing the samples of an NTSC composite signal and the 2D Hadamard transform $F(u, v)$ can be expressed by

$$F(u, v) = \frac{1}{N^2} H_N f(x, y) H_N \tag{1}$$

$$f(x, y) = H_N F(u, v) H_N \tag{2}$$

where the indices u and v correspond to variations in the horizontal and vertical directions, respectively. The result of the 2D Hadamard transform is a $N \times N$ coefficient matrix whose coefficients represent the projection of the data matrix onto the particular Hadamard basis picture. The 8×8 Hadamard matrix with rows and columns arranged with increasing sequency is usually referred to

© IEE, 1994

Paper 9843K (E4, E14), first received 1st April and in revised form 9th September 1993

M. Colef is with the Department of Electrical Engineering, New York Institute of Technology, HSH Building, Room 226F, Old Westbury, NY 11568, USA

J. Barba is with the Department of Electrical Engineering, The City College of New York, 140th Street and Convent Avenue, New York, NY 10031, USA

as the ordered Hadamard matrix and is given [8, 9] by

$$H_8 = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & -1 & -1 & -1 & -1 \\ 1 & 1 & -1 & -1 & -1 & -1 & 1 & 1 \\ 1 & 1 & -1 & -1 & 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 & 1 & -1 & -1 & 1 \\ 1 & -1 & -1 & 1 & -1 & 1 & 1 & -1 \\ 1 & -1 & 1 & -1 & -1 & 1 & -1 & 1 \\ 1 & -1 & 1 & -1 & 1 & -1 & 1 & -1 \end{bmatrix} \quad (3)$$

and the corresponding basis pictures are shown in Fig. 1.

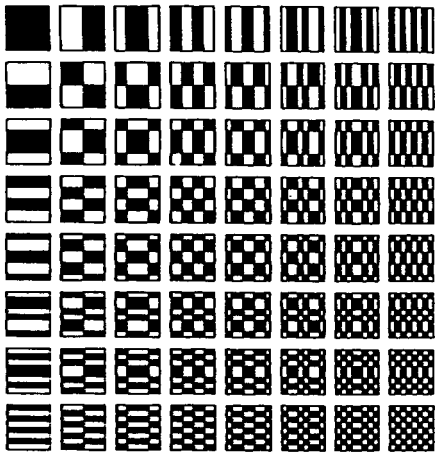

Fig. 1 *Two-dimensional basis pictures for Hadamard vectors of dimension 8*
black = 1, white = −1

The NTSC composite colour signal is given by

$$\begin{aligned} f(t) &= Y(t) + I_m(t) + Q_m(t) \\ &= Y(t) + I(t) \cos(2\pi f_{sc} t + 33°) \\ &\quad + Q(t) \sin(2\pi f_{sc} t + 33°) \end{aligned} \quad (4)$$

where $Y(t)$ represents the luminance signal; $I(t)$ and $Q(t)$ are the chrominance baseband signals; $f_{sc} = 3.579$ MHz $= (227 + 1/2) f_h$ is the colour subcarrier and f_h is the horizontal line frequency of 15.734 KHz. A consequence of the scanning rates is that the phase of the modulating subcarrier changes 180° from line to line. The luminance and chrominance information occupy the same channel spectrum with the luminance component containing most of the signal energy and having frequency components which are, on average, located in narrow bands around harmonics of the horizontal line frequency. The chrominance signals are modulated in quadrature and transmitted on the colour subcarrier at $(455/2) f_h$ and contain most of their energy in bands around odd multiples of half the line frequency [10]. In general, there is an overlap of the chrominance and luminance spectra, and the NTSC composite signal cannot be separated exactly into the original components. Transform coders that operate on the components of the NTSC video signal usually accomplish the separation by using either an analogue or digital comb filter [11–14].

From a heuristic point of view, consider that the component signals have constant values. Then, if the NTSC composite signal is sampled at $4f_{sc}$ and the sampling occurs at 12°, 102°, 192°, and 282° of the subcarrier, the resulting sampled composite signal will be

$$f(nT) = Y(nT) + I(nT) \cos(n\pi/4) + Q(nT) \sin(n\pi/4)$$
$$n = 1, 2, 3, \ldots \quad (5)$$

where $T = 1/4f_{sc}$. The samples modulated I and Q signals are shown in Fig. 2. If we consider an 8 × 8 Hadamard transformation, we notice that the sampled modulated Q and I signals shown in Fig. 2 correspond

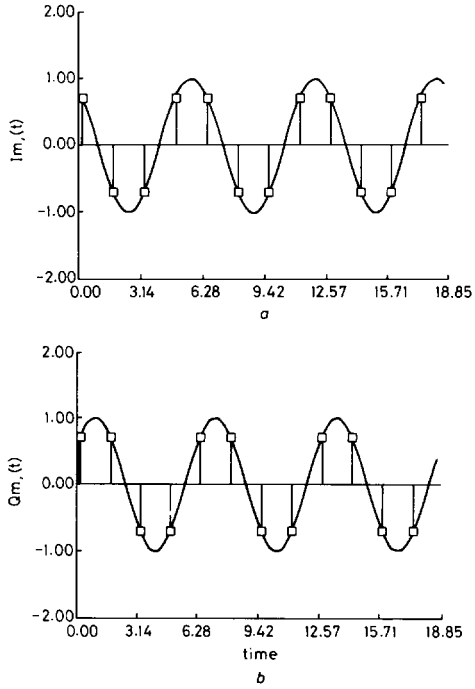

Fig. 2 *Modulated constant I and Q signals sampled at proper phase*
a sampled *I*
b sampled *Q*

exactly, in the horizontal direction, to the Hadamard basis vectors of sequency 3 and 4, respectively. This means that the 8 × 8 matrix $f(x, y)$, obtained from the sampled composite signal will project the chrominance signal energy along columns 4 and 5 of the coefficient matrix $F(u, v)$, which correspond to the basis pictures with horizontal sequency of 3 and 4. In the vertical direction, the chrominance signal corresponds to the Hadamard basis vector of the highest sequency owing to the 180° phase shift of the colour subcarrier from line to line in each field. Thus, the chrominance signal energy must be mapped along row 8 of the coefficient matrix. The result is that the DC value of the modulated Q and I signals will be mapped onto coefficients (3, 7) and (4, 7) of the 8 × 8 Hadamard transform, respectively.

The above results can be generalised for any $I(t)$ and $Q(t)$. Here we make the initial assumption that the component signals, when partitioned into $N \times N$ blocks, maintain their original bandwidth (i.e. we do not initially worry about the effects of data discontinuity due to data truncation and resulting energy leakage). The effect of sampling the modulated I and Q signals is equivalent to spatially multiplying the baseband I and Q signals by the

corresponding modulation matrix. The modulation matrices for the Q and I signals for a 4 × 4 picture block are

$$M_Q^4 = \begin{bmatrix} 1 & 1 & -1 & -1 \\ -1 & -1 & 1 & 1 \\ 1 & 1 & -1 & -1 \\ -1 & -1 & 1 & 1 \end{bmatrix}$$

and (6)

$$M_I^4 = \begin{bmatrix} 1 & -1 & -1 & 1 \\ -1 & 1 & 1 & -1 \\ 1 & -1 & -1 & 1 \\ -1 & 1 & 1 & -1 \end{bmatrix}$$

For transform size greater than 4 × 4 the corresponding modulation matrices are given by

$$M_L^{2^k} = \begin{bmatrix} M_L^{2^{k-1}} & M_L^{2^{k-1}} \\ M_L^{2^{k-1}} & M_L^{2^{k-1}} \end{bmatrix} \quad L = \begin{cases} Q \\ I \end{cases} \quad k = 3, 4, \ldots \tag{7}$$

Thus, an $N \times N$ array of the sampled chrominance signals can be written as

$$\sqrt{(2)} L_m = L \otimes M_L^N \quad L = Q \text{ or } I \tag{8}$$

where L and L_m represent $N \times N$ sample arrays of the baseband and modulated chrominance signals, respectively; M_L^N is the $N \times N$ modulation matrix corresponding to the particular chrominance signal in eqn. 8; and $\otimes$ denotes spatial multiplication (i.e. $L_m(i, j) = L(i, j) M_L^N(i, j)$; $i, j = 0, 1, 2, \ldots, N$.

The modulation matrices of eqn. 8 can be separated into two operators, one operating on the rows of the data and the other operating on the columns of the data. Thus, eqn. 8 can be written as

$$\sqrt{(2)} L_m = {}_V M_L^N \otimes L \otimes {}_H M_L^N \quad L = \begin{cases} Q \\ I \end{cases} \tag{9}$$

where ${}_V M_L^N$ is an $N \times N$ matrix whose columns are all equal to the Hadamard vector with sequency $N - 1$, $\text{Wal}_{N-1}(y)$, and ${}_H M_L^N$ is an $N \times N$ matrix whose rows are all equal t the vectors $\text{Wal}_{(N/2)-1}(x)$ when $L = Q$ or $\text{Wal}_{(N/2)}(x)$ when $L = I$.

To obtain a complete mapping of the modulated chrominance signals in the Hadamard domain let the $N \times N$ transform of $I(t)$ and $I_m(t)$ be given by

$$F_I = \frac{1}{N^2} H_N I H_N \tag{10}$$

$$F_{I_m} = \frac{1}{N^2} H_N I_m H_N \tag{11}$$

Eqn. 11 can be expressed with respect to the baseband signal and the modulation matrix by

$$\begin{aligned} F_{I_m} &= \frac{1}{N^2 \sqrt{(2)}} H_N (I \otimes M_I^N) H_N \\ &= \frac{1}{N^2 \sqrt{(2)}} H_N ({}_V M_I^N \otimes I \otimes {}_H M_I^N) H_N \\ &= \frac{1}{N^2 \sqrt{(2)}} (H_N \otimes {}_V M_I^N) I ({}_H M_I^N \otimes H_N) \end{aligned} \tag{12}$$

Since the spatial product of two Hadamard basis vectors with sequency a and b results in another basis vector given by

$$\text{Wal}_a(x) \otimes \text{Wal}_b(x) = \text{Wal}_{a \oplus b}(x) \tag{13}$$

where $\oplus$ represents sum modulo 2 (i.e. $1 + 0 = 0 + 1 = 1$ and $0 + 0 = 1 + 1 = 0$), eqn. 12 can be expressed as

$$F_{I_m} = \frac{1}{\sqrt{(2)}} F(u \oplus (N/2), v \oplus (N - 1)) \tag{14}$$

In general, the $N \times N$ transform of I_m and Q_m are related to the transforms of baseband I and Q signals by

$$F_{L_m}(u, v) = \frac{1}{\sqrt{(2)}} F_L(u \oplus k, v \oplus (N - 1))$$

$$L = \begin{cases} Q \\ I \end{cases} \quad k = \begin{cases} (N/2) - 1 & L = Q \\ (N/2) & L = I \end{cases} \tag{15}$$

Eqn. 15 relates the transform mapping of the baseband chrominance signal to the mapping of the modulated chrominance signal in the Hadamard domain; having one mapping the other can be obtained. Eqn. 15 indicates that higher frequency components of the modulated Q and I signals are projected along opposite directions along a row (i.e. the higher frequency components of the modulated Q signal are represented by coefficients to the left of coefficient (3, 7) whereas higher frequency components of the modulated I signal are represented by coefficients to the right of coefficient (4, 7)). Since the baseband Q and I signals are bandlimited to 0.5 MHz and 1.5 MHz respectively, the transform should ideally have zero value for those coefficients which represent frequency variations greater than the highest frequency component of the baseband signal. The effect of truncating the data by an $N \times N$ window when performing the 2D transform is to introduce energy leakage into the higher frequency components of the Hadamard domain. This results in an overlapping of the component spectrums in the Hadamard domain and prevents complete separation of the components.

3 Simulation results

An example of the mapping of the chrominance signals in the Hadamard domain is shown in Fig. 3. All simulations were performed using real double precision arithmetic. The NTSC colour bars signal was sampled at $4f_{sc}$ and proper phase. Fig. 3*a* shows the vector diagram for the original colour bars signal which was transformed using an 8 × 8 Hadamard transform. Fig. 3*b* shows the result of setting the coefficients (2, 7), (3, 7), and (3, 6) to zero. Since these coefficients correspond to the Q signal, the only colour information lies along the I axis. Similarly, Fig. 3*c* shows the result of setting coefficients (4, 7), (5, 7) and (4, 6) to zero. Here, the resulting colour information lies along the Q axis. To facilitate separation of the NTSC, components particular coefficients have to be assigned to each component. Various criteria can be used to assign coefficients or even portions of coefficient to each component. Since we wish only to demonstrate the technique of component separation in the Hadamard domain, the standard deviation was used to determine the coefficient assignment. The standard deviation equals the positive square root of the variance given by

$$\sigma^2 = \frac{1}{T} \sum_{r=1}^{T} [F_r(i, j) - \bar{F}(i, j)]^2 \tag{16}$$

where T represents the total number of transform matrices; $F(i, j)$ the (i, j)th coefficient in the rth transform

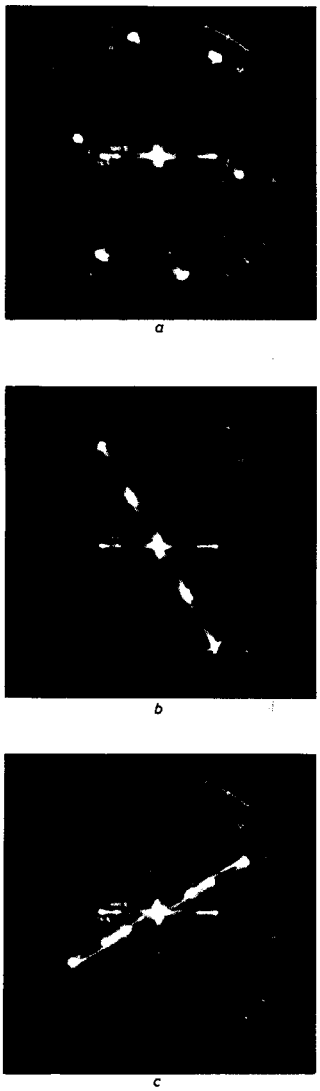

Fig. 3 *Vector scope waveforms*
a NTSC composite colour bars signal sampled at $4f_{sc}$
b result of inverse Hadamard transform after setting coefficients (2, 7), (3, 7) and (3, 6) to zero in 8 × 8 transform
c result of inverse Hadamard transform after setting coefficients (4, 7), (5, 7) and (4, 6) to zero in 8 × 8 transform

matrix; and $\bar{F}(i, j)$ the average value of the (i, j)th coefficient. Five colour images were used to obtain the average coefficient standard deviations. Four of the images are the standard test slides SMPTE1, SMPTE2, SMPTE3, and SMPTE15. The fifth image is that of a *boy* playing with toys. The three signals $Y(t)$, $I(t)\cos(2\pi f_{sc}t + 33°)$, and $Q(t)\sin(2\pi f_{sc}t + 33°)$ were generated and Hadamard transformed for each of the five images. The standard deviation for the three signals averaged over the active video portion of the five images are given in Table 1. The effect of windowing and truncation of the data results in the energy of the baseband signals being spread over the Hadamard domain. A particular coefficient is assigned to the component which has the largest standard deviation for the particular coefficient. The resulting coefficient

Table 1: Average standard deviation of 8 × 8 transform coefficients of composite signals for five NTSC images

			a Y				
33.565	5.239	2.379	2.399	0.705	0.866	1.083	1.227
8.633	2.954	1.559	1.351	0.589	0.657	0.733	0.668
5.012	2.132	1.226	1.001	0.517	0.565	0.590	0.500
4.295	1.745	1.009	0.823	0.451	0.496	0.497	0.426
2.353	1.238	0.795	0.653	0.427	0.425	0.414	0.351
2.334	1.130	0.731	0.603	0.417	0.419	0.402	0.339
2.227	1.024	0.641	0.558	0.401	0.385	0.369	0.324
1.908	0.735	0.490	0.471	0.429	0.344	0.323	0.290
			b I_m				
0.037	0.046	0.053	0.440	0.487	0.186	0.109	0.080
0.035	0.049	0.058	0.050	0.517	0.214	0.118	0.092
0.036	0.051	0.061	0.051	0.504	0.228	0.126	0.096
0.037	0.052	0.064	0.054	0.518	0.243	0.132	0.101
0.038	0.057	0.073	0.068	1.009	0.309	0.153	0.132
0.042	0.062	0.083	0.078	1.045	0.363	0.176	0.156
0.047	0.069	0.101	0.111	1.920	0.508	0.216	0.223
0.062	0.097	0.143	0.230	8.810	1.026	0.306	0.463
			c Q_m				
0.048	0.042	0.087	0.260	0.032	0.030	0.030	0.033
0.055	0.046	0.105	0.306	0.034	0.031	0.030	0.031
0.057	0.049	0.112	0.341	0.035	0.032	0.030	0.031
0.063	0.051	0.126	0.373	0.037	0.033	0.031	0.031
0.075	0.057	0.151	0.507	0.042	0.035	0.032	0.032
0.080	0.064	0.166	0.555	0.045	0.037	0.032	0.032
0.091	0.073	0.190	0.766	0.050	0.041	0.033	0.033
0.154	0.091	0.322	2.775	0.079	0.049	0.036	0.035

assignment for a 4 × 4, 8 × 8 and 16 × 16 transform matrix size are given in Table 2.

We notice from Table 1 that the modulated Q and I coefficients are assign locations which normally represent the high frequency of the Y signal. To see the effect on the Y signal of setting these coefficients equal to zero, we used the *test* pattern shown in Fig. 4. Fig. 4*a* is the original *test* pattern sampled at $4f_{sc}$. The reason the entire image is not present in the horizontal direction is that our imaging system only stores 512 samples per line. Figs. 4*b*, *c* and *d* are processed images using a 4 × 4, 8 × 8 and 16 × 16 Hadamard transform, respectively. These images were obtained by performing the appropriate size Hadamard transform of the original sampled NTSC image, setting to zero the coefficients assigned to the Q and I signals in Table 2, and performing the

Table 2: Coefficient assignment for Q_m and I_m, all other coefficients are assigned to Y

Matrix size	Q_m	I_m
4 × 4	(1, 3)	(2, 3), (3, 3)
8 × 8	(2, 7), (3, 7), (3, 6) (3, 5)	(4, 7), (5, 7), (6, 7), (7, 7), (4, 6), (5, 6), (4, 5), (4, 4)
16 × 16	(6, 15), (7, 15), (6, 14), (7, 14), (7, 13), (7, 12), (7, 11), (7, 10), (7, 9), (7, 8)	(8, 15), (9, 15), (10, 15), (11, 15), (8, 14), (9, 14), (10, 14), (11, 14), (8, 13), (9, 13), (10, 13), (11, 13), (8, 12), (9, 12), (8, 11), (9, 11), (8, 10), (9, 10), (8, 9), (9, 9), (8, 8), (8, 7), (11, 8), (8, 6), (8, 5), (8, 4), (8, 3)

inverse Hadamard transform. The original and processed images were shown on a monochrome monitor to 10 unbiased viewers who had no image processing background. All ten viewers had trouble determining which images were 'better'. When told what to look for, they were barely able to see the staircase effect on the edges in the 4 × 4 processed image. This is especially evident in Fig. 4*b* towards the centre and those lines which form a

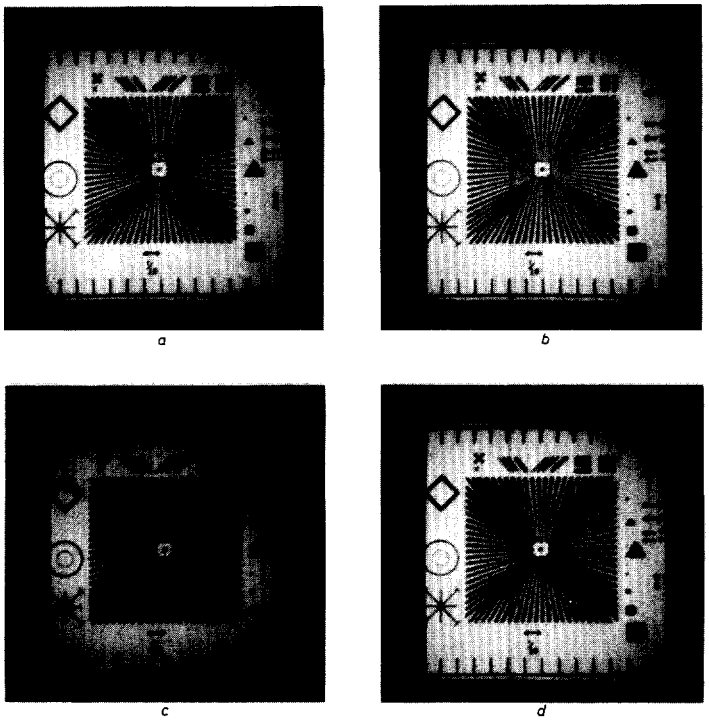

Fig. 4 *Original monochrome test pattern sampled at $4f_{sc}$ and inverse Hadamard transform images after setting I and Q coefficients listed in Table 2 to zero*

a original *b* 4 × 4 transform *c* 8 × 8 transform *d* 16 × 16 transform

45° angle with the base of the image where high frequencies are required in the image. Four of the viewers could see 'some' degradation of the 8 × 8 transform image and none could see any degradation of the 16 × 16 image. Judging from the response of the viewer and the knowledge that typical scenes do not have such high frequency content as Fig. 4*a*, we believe that the degradation of the luminance signal when separated using the Hadamard transform will not be noticeable. The degradation introduced by excluding from the luminance signal those coefficients assign to the modulated *Q* and *I* signals generally correspond to line patterns oriented at 45°; precisely the patterns the eye has low acuity for. Additionally, use of this technique on moving images would tend to integrate out the effects of artefacts and reduce their visibility in bandwidth compression, where some degradation is expected, this technique of separating the luminance signal should prove more than adequate.

To see the effects on the chrominance signals, we sampled the NTSC composite signal with proper phase at $4f_{sc}$ and performed the component separation in the Hadamard domain as outlined below.

(*a*) Set to zero those coefficients which do not correspond to the particular signal being recovered.

(*b*) If either of the chrominance signals is being recovered, multiply the coefficients by $\sqrt{(2)}$ and remap the coefficients by the inverse operation of eqn. 15.

(*c*) Perform the inverse Hadamard transform to obtain the recovered baseband signal. The separated components were used to reconstruct the NTSC composite image for subjective viewing.

The signal-to-noise ratio (SNR) of the recovered signals can be expressed [4] as

$$\text{SNR} = -10 \log \left[\frac{\frac{1}{N} \sum_{j=1}^{N} (S_j - \hat{S})^2}{255^2} \right] \tag{17}$$

where N represents the total number of samples in the image, S and $\hat{S}$ represent the original and recovered baseband signals, respectively. The resulting SNRs obtained using the Hadamard transform are presented in Table 3. We notice that the component separation generally improves as the transform size increases. This results because, as the window increases in size, less high frequency energy is generated from convoluting the signal and window spectrum.

Fig. 5 shows the original *boy* image and the processed image using a 4 × 4, 8 × 8, and 16 × 16 Hadamard transform. The processed images were obtained by properly sampling the original NTSC composite signal;

Table 3: SNR (dB) of component signals after reconstruction

		SMPTE1	SMPTE2	SMPTE3	SMPTE15	BOY
4 × 4	*Y*	40.54	39.84	40.80	41.95	39.13
	I	40.22	39.38	40.02	41.82	38.06
	Q	41.27	39.90	41.75	42.62	39.87
8 × 8	*Y*	41.37	40.03	41.53	42.73	39.57
	I	40.52	39.53	40.30	42.08	38.51
	Q	42.76	40.17	43.17	43.95	40.22
16 × 16	*Y*	41.26	40.63	41.62	42.38	39.57
	I	42.99	39.77	39.95	41.68	38.60
	Q	42.99	41.17	43.19	43.88	42.36

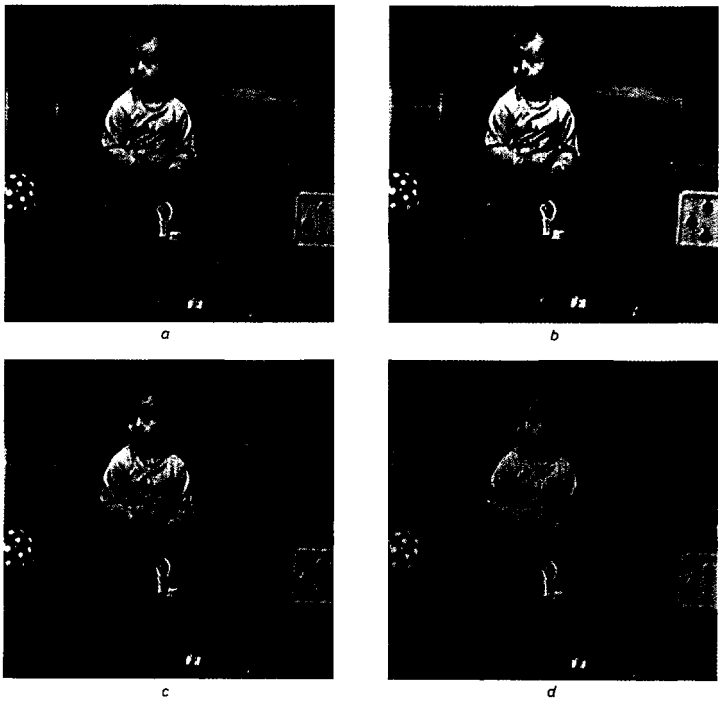

Fig. 5 *Generation of composite image using YIQ signals obtained by component separation in Hadamard domain using coefficient allocation of Table 2*

a original *b* 4 × 4 transform *c* 8 × 8 transform *d* 16 × 16 transform

taking the appropriate size Hadmard transform, performing the component separation described above; and then using the separated components to generate the composite images presented in Figs. 5*b–d*. The processed images were viewed on a Sony Trinitron monitor model CVM-1750. No degradation was noticeable in any of the processed images. No difference in colour content was detected. The processed colours remained saturated and showed no streaking or bleeding.

4 Conclusions

This paper presented a technique by which component separation of NTSC composite signal can be achieved in the Hadamard domain by sampling the composite signal at four times the colour subcarrier. The only constraint is the sampling phase relative to the colour subcarrier which poses no problem in implementation. This technique does not require the additional equipment that is normally needed to demodulate the component signals prior to transform coding. Component coding is performed by allocating bits to the appropriate transform coefficients of the composite signal. At the receiver all that is required is performing an inverse transformation to reconstruct the NTSC composite signal. Results of component separation of the six images used indicate that the procedure should produce no noticeable degradation in typical images.

Application of the technique presented in this paper to PAL signals would map the luminance energy similar to a NTSC signal. The mapping of chrominance signal energy would be more towards the centre of the coefficient matrix making separation more difficult [15]. In SECAM, the situation is made more difficult by the fact that the chrominance signals are frequency modulated. We are not aware of any transform technique, similar to the one presented here, which was applied to SECAM.

5 References

1 LIMB, J.O., RUBENSTEIN, C.B., and THOMPSON, J.E.: 'Digital coding of color video signals: a review', *IEEE Trans.*, 1977, **COM-25**, pp. 1349–1385

2 MUSMANN, H.G., PIRSCH, P., and GRALLERT, H.-J.: 'Advances in picture coding', *Proc. IEEE*, 1985, pp. 523–548

3 EKAMBARAM, C., and KWATRA, S.C.: 'A new architecture for adaptive transform compression of NTSC composite video', *NTC*, 1981, pp. C9.6.1–C9.6.5

4 PLOYSONGSANG, A., and RAO, K.R.: 'DCT/DPCM processing of NTSC composite video signals', *IEEE Trans.*, 1982, **COM-30**, pp. 541–549

5 KWATRA, S.C., and FATMI, H.: 'NTSC composite video at 1.6 Bits/Pel'. ICC, 1983, pp. B4.6.1–B4.6.5

6 PRATT, W.K.: 'Image transmission techniques' (Academic Press, 1979)

7 KNAUER, S.C.: 'Real-time video compression algorithm for Hadamard transform processing', *IEEE Trans.*, 1976, **EMC-18**

8 HALL, E.L.: 'Computer image processing and recognition' (Academic Press, 1979)

9 HARMUTH, H.F.: 'Sequency theory foundations and applications' (Academic Press, 1977)

10 BROB, B.: 'Basic television principles and servicing' (McGraw-Hill, 1975, 4th edn)

11 SAUER, D.J.: 'Design and performance of a CCD comb filter IC', *RCA Rev.*, 1980, **41**, pp. 29–56

12 STENGER, L.: 'Digital comb-filter demodulation of PAL color television signals', *IEEE Trans.*, 1979, **COM-27**, pp. 1624–1631

13 SAWADA, K., and KOTERA, H.: 'A 32 Mbit/s component separation DPCM coding system for NTSC Color TV', *IEEE Trans.*, 1978, **COM-26**, pp. 458–465

14 ISHIGURO, T., IINUMA, K., IIJIMA, Y., KOGA, T., AZAMI, S., and MUNE, T.: 'Composite interframe coding of NTSC television signals'. NTC, 1976

15 CLARKE, R.J.: 'Transform coding of images' (Academic Press, 1985)